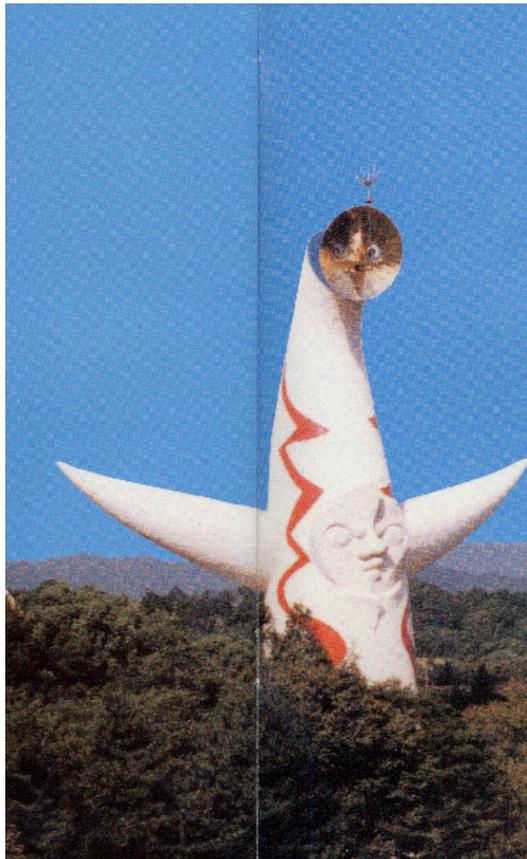


High Repetition High Average Power Nd:YAG Laser System for EUV Lithography



H. Fujita,

K. Tsubakimoto, H. Yoshida, A. Mitra, T. Wang,
Y. Fujimoto, M. Nakatsuka, N. Miyanaga, and Y. Izawa

ILE, Osaka University

S. Matsuoka, H. Kubomura, T. Kasamatsu, T. Uchiyama,
H. Miyajima, and H. Kan

Hamamatsu Photonics



What is EUV Laser ? Why at ILE ?

Requirements for EUV Laser

Output Energy	: 1 - 3 J/pulse	→ 2 - 6 J/cm ²
Pulse Duration	: 1 - 10 ns	
Repetition Rate	: 5 - 20 kHz	
Stability	: ± 0.3 % (3σ, Ave. of 50 pulse)	

Concepts of ILE, Osaka Univ.

Oscillator	: Fiber Laser (Reliability & Stability)
Main Amplifier	: Rod (or Disk) Pumped by CW LDs

Strong and Uniform Pumping

→ Thermal Fracture Limit, Thermal Effects

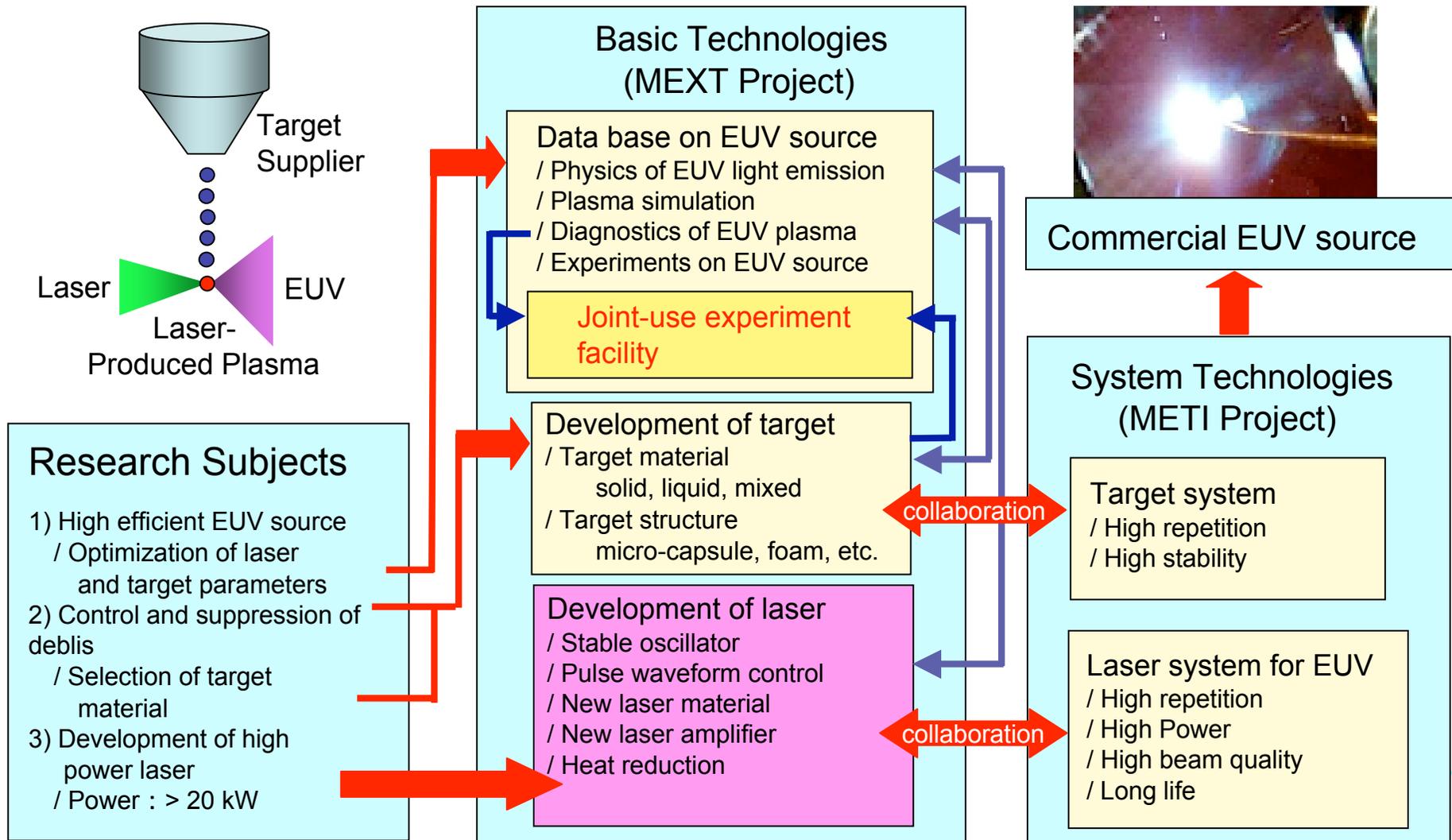
System	: Computer Control (Alignment, Compensation of Thermal Effects)
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Future Driver for Laser Fusion

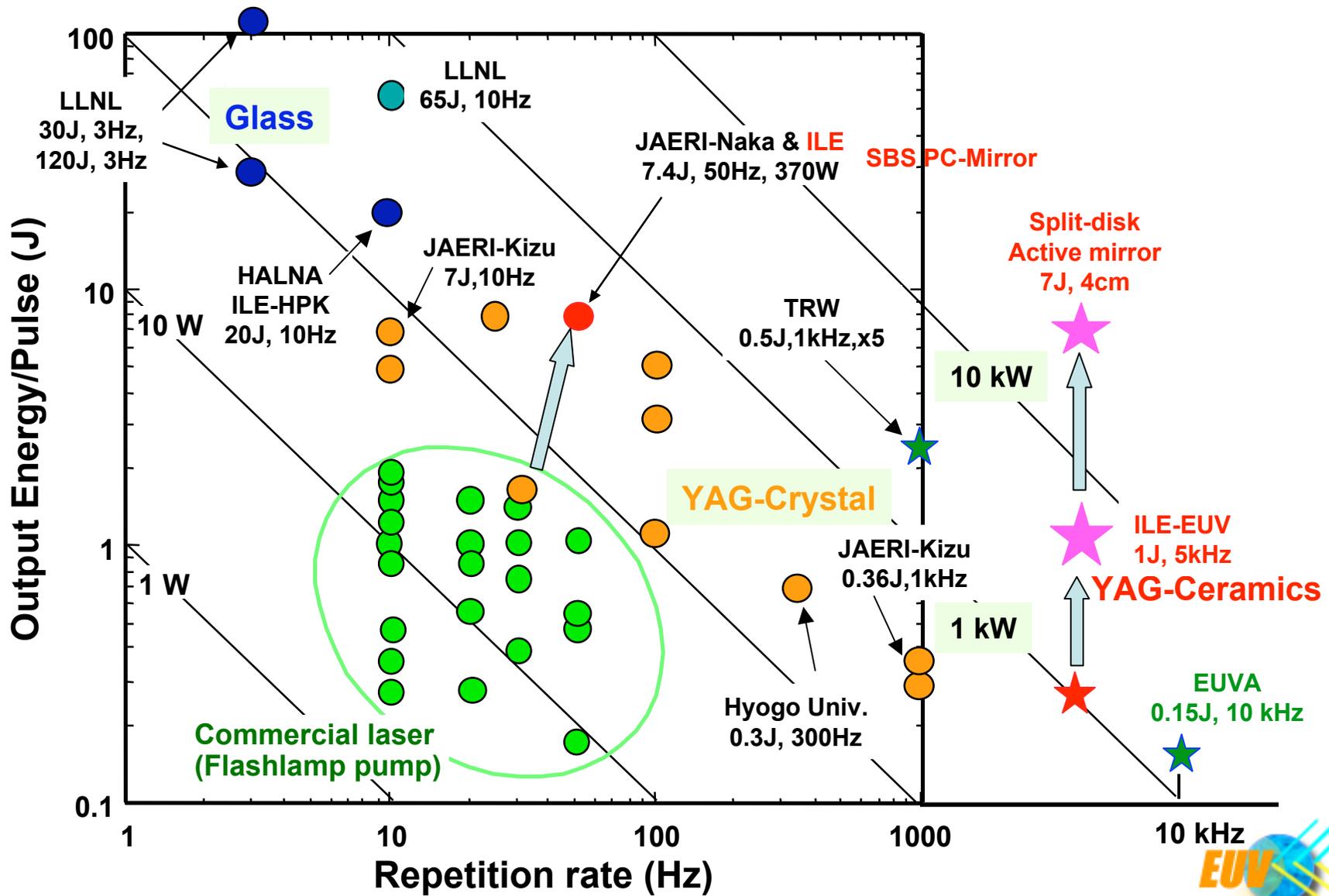


Project on Extreme Ultra Violet Light Source Development

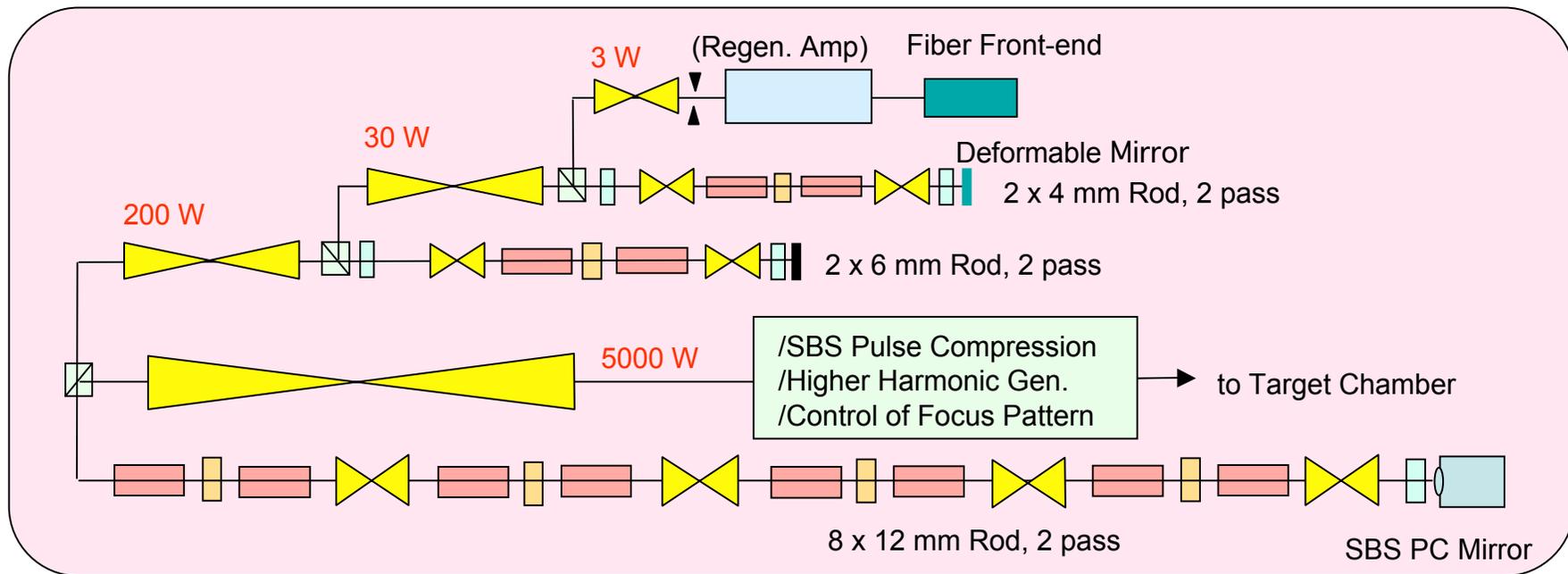
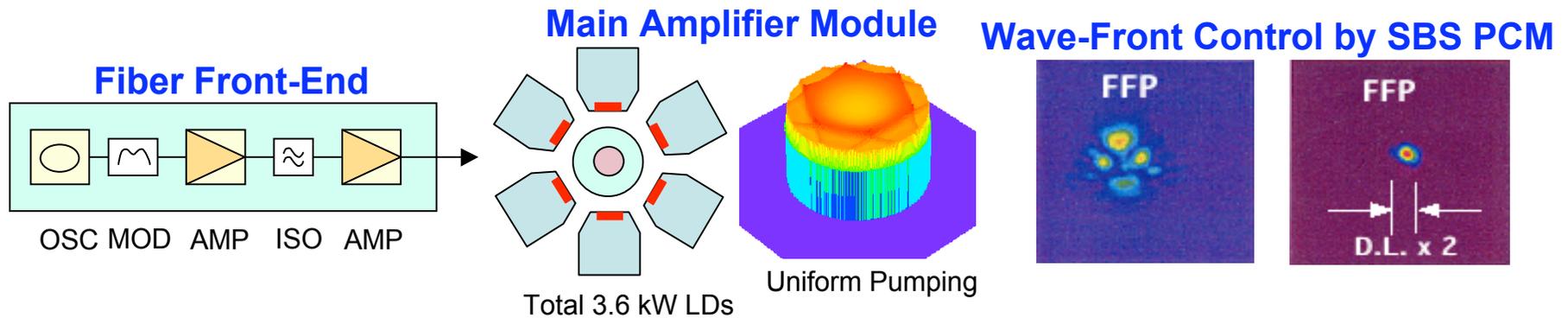
EUV light source and laser fusion research are standing on common scientific bases. ILE Osaka-U. has started EUV light source development.



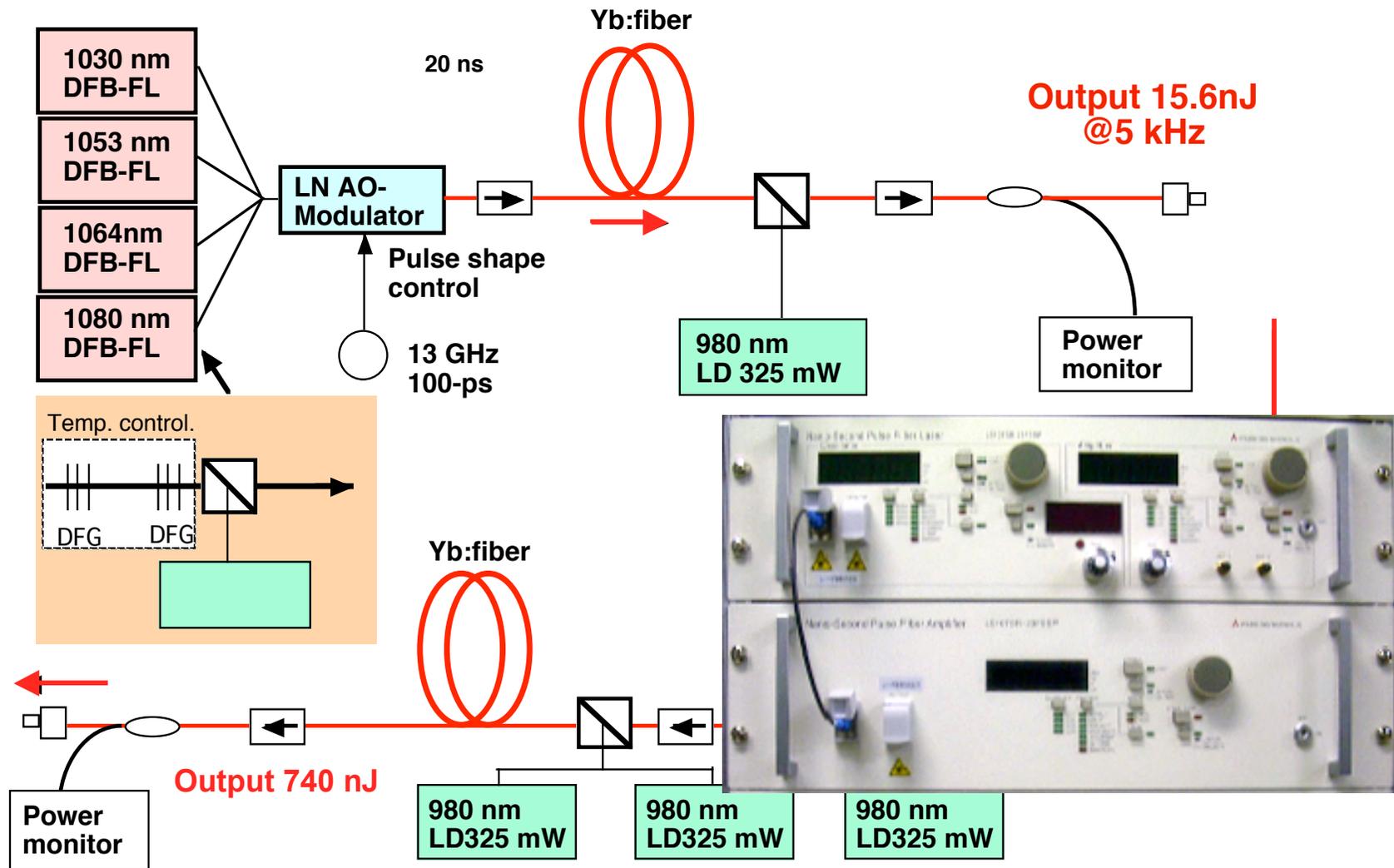
High Average Power Pulse Laser in the World



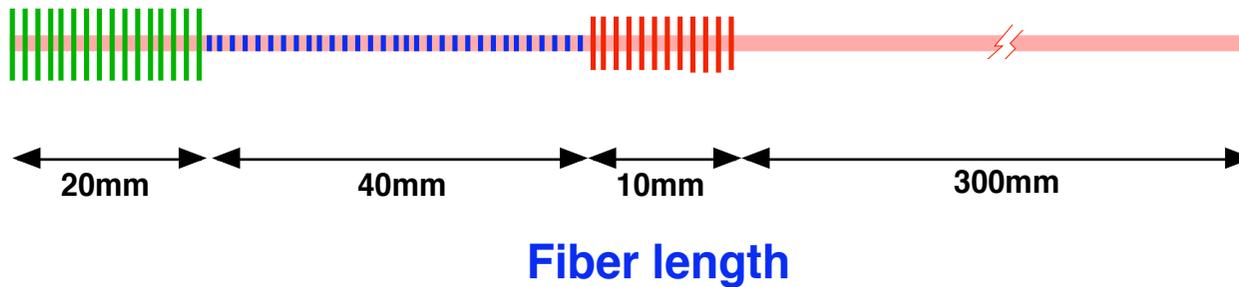
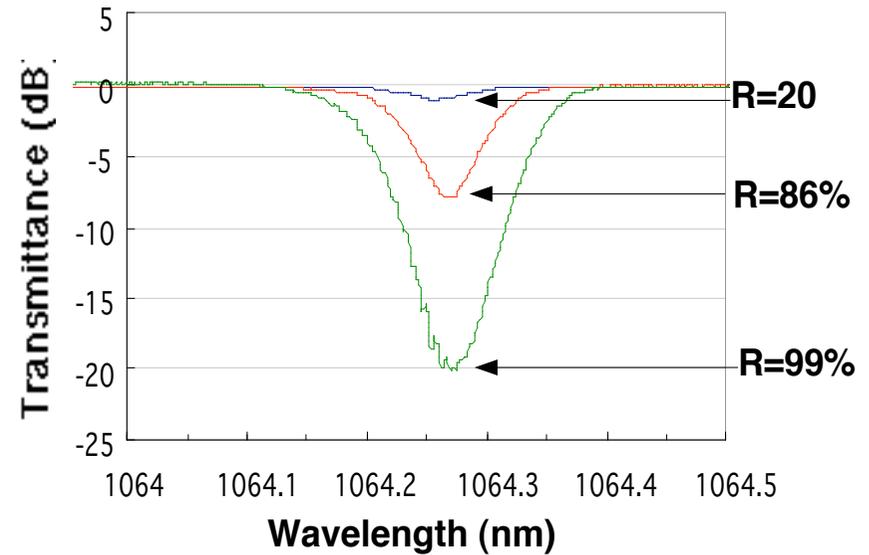
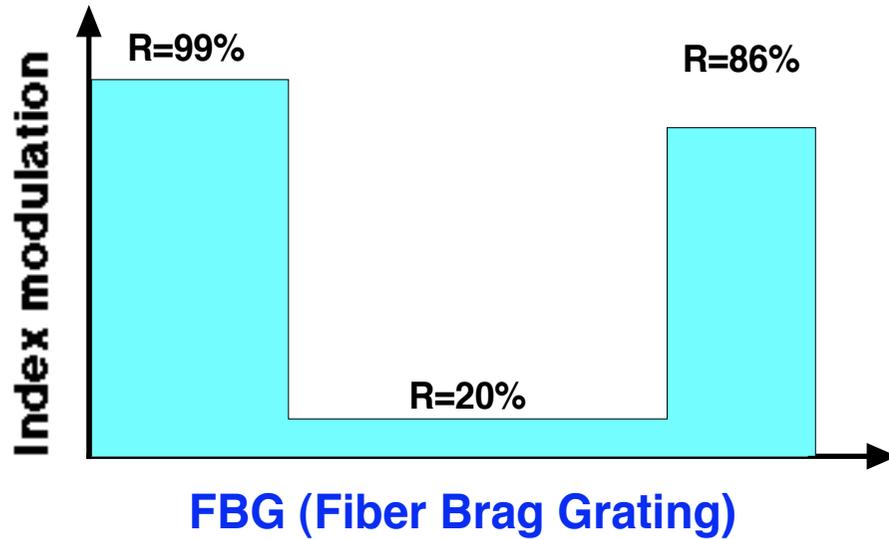
5 kW (1J / 5 kHz) Laser System for EUV Lithography



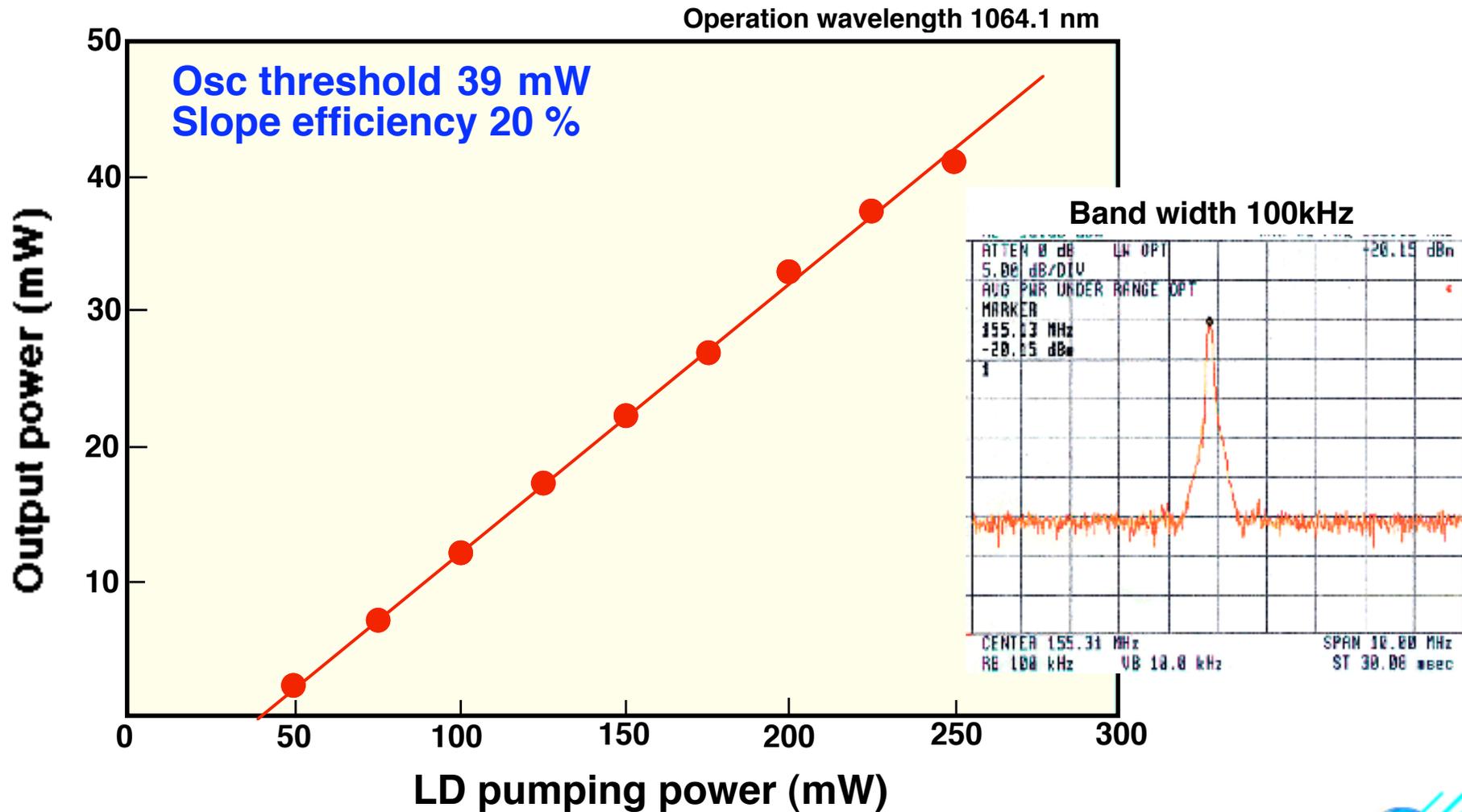
Layout of Yb: fiber oscillator and amplifier system



Single-longitudinal mode Yb-silica fiber oscillator by FBG



CW output power as a function of pumping power



Summary (Frontend)

Development of Yb:silica fiber master oscillator and amplifier system

Single longitudinal mode oscillation by FBG (fiber bragg garting)

Band width 100kHz

Turning range 1030, 1053, 1064, 1080 \pm 0.5 nm

Extremely precise 0.1 pm

CW output power 40 mW (slope efficiency 20 %)

Switch out by EO modulator 1 - 3 ns

Pulse output energy 740 nJ, 3 ns (@5 kHz)

Development of CW pumped Nd:YAG regenerative amplifier system

Output beam quality TEM₀₀ mode, $M^2=1.1$

Maximum output energy 1.12 mJ (@1 kHz), $G= 3.7 \times 10^5$

Maximum output power 5.3 W (@5 kHz)

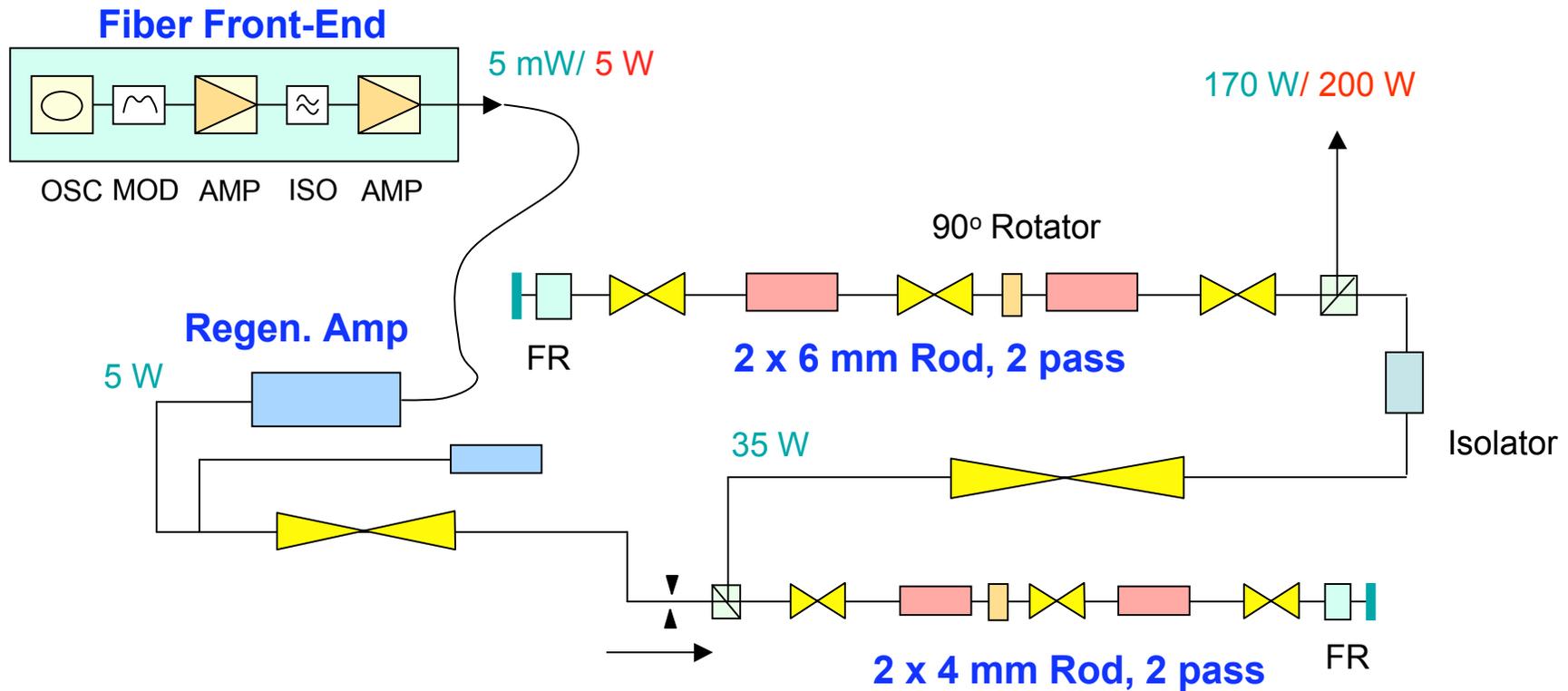
(1) High-average-power Yb: fiber laser system

Output power 5W(@1mJ, 5kHz)

(2) Arbitrary pulse shape control



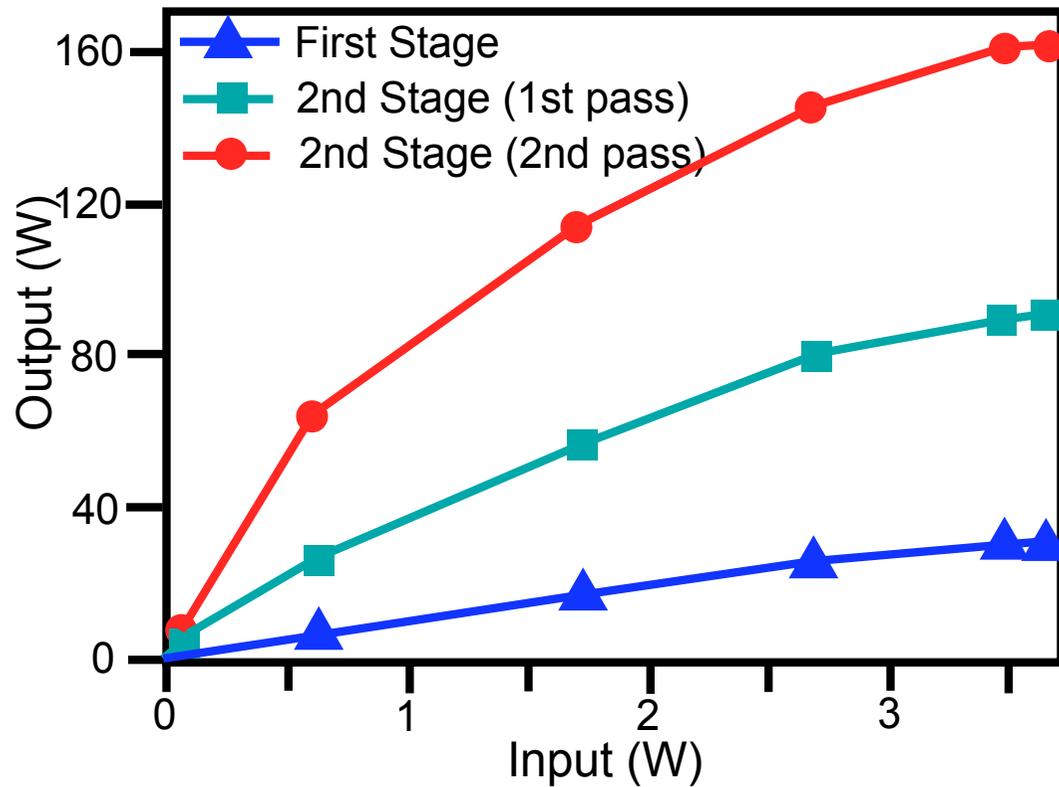
Optical Layout of Pre-amplifiers



Input pulses: 10 ns or 300 ps, 5 kHz



Amplification Property of Pre-amplifiers



Input pulse: 10 ns, 5 kHz | 300ps, 5kHz
 Output power: ~ 170 W | ~ 80W

Thermal lens: 200 - 1200 mm
 compensated by image relaying optics

Far-field (upper) and Near-field (lower) pattern

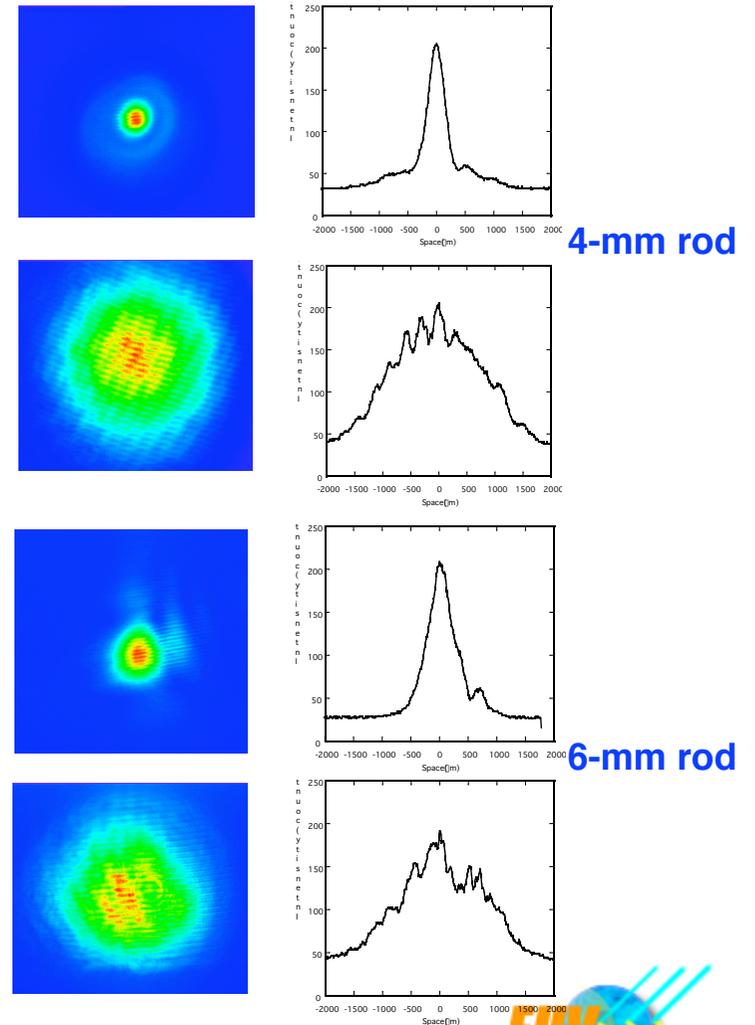
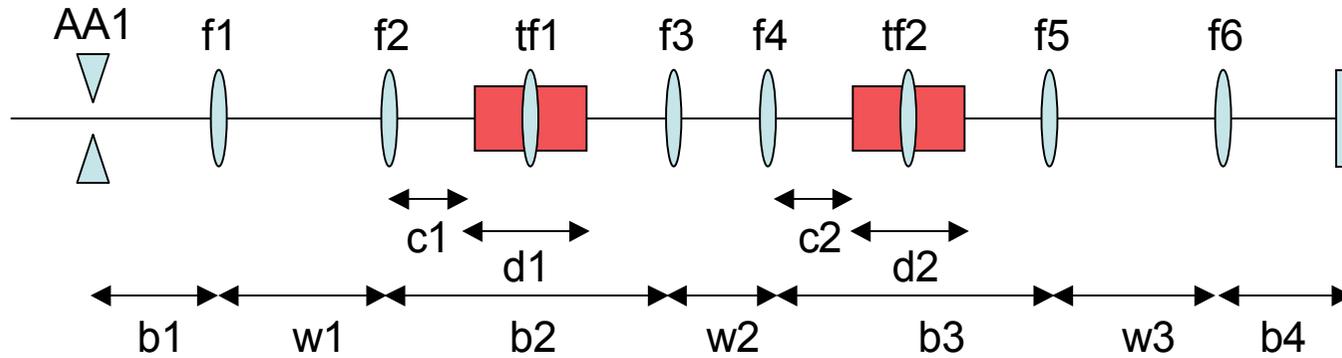
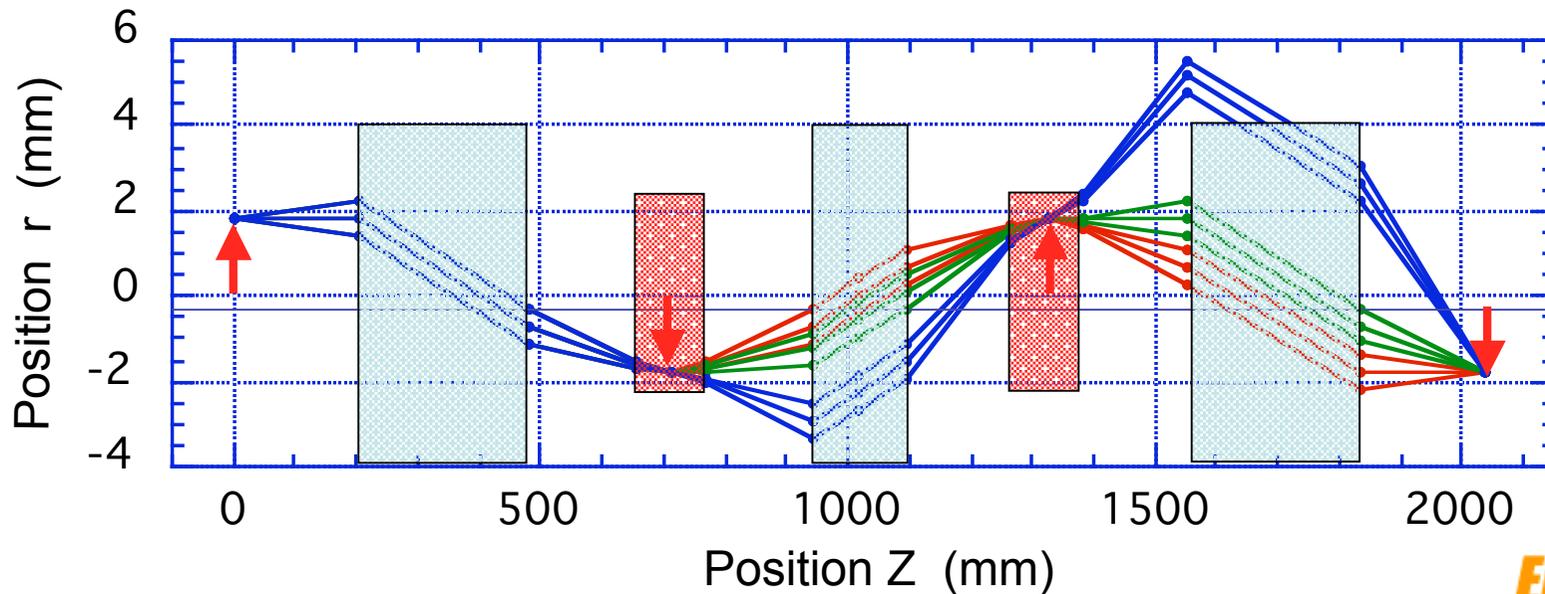


Image Relay and Thermal Lens Compensation



- Thermal Lens $f = 20$ cm
- Thermal Lens $f = 30$ cm
- Thermal Lens $f = \infty$ cm

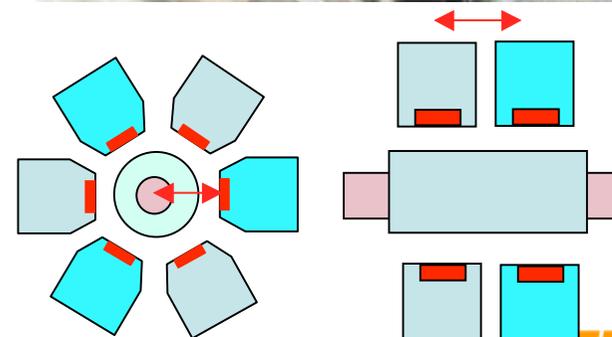
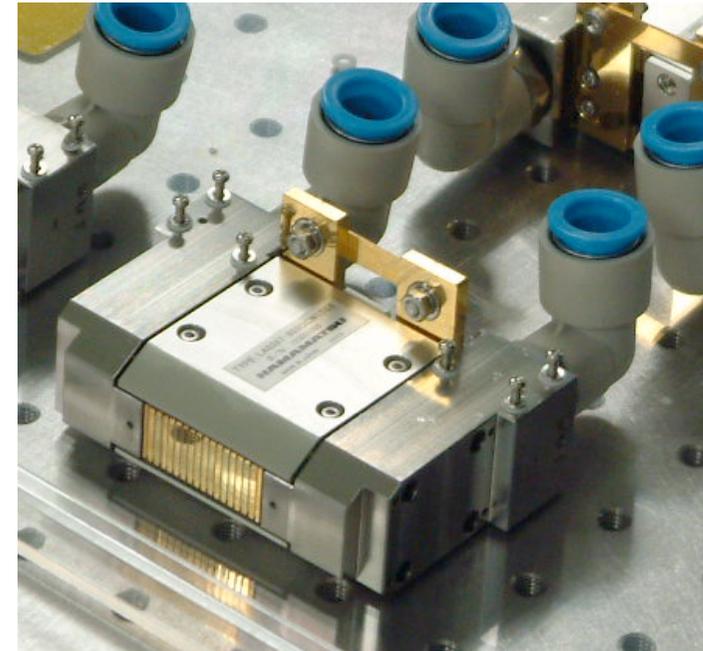
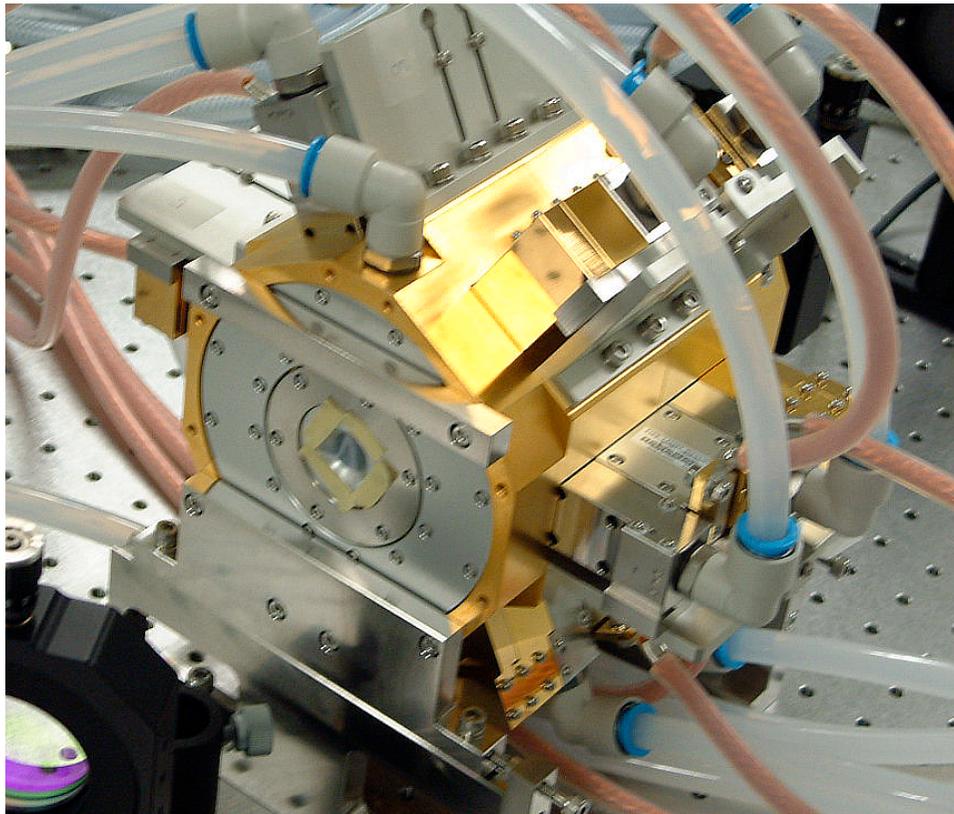


Test Amplifier Module

Nd: YAG pumped by Pulse LD

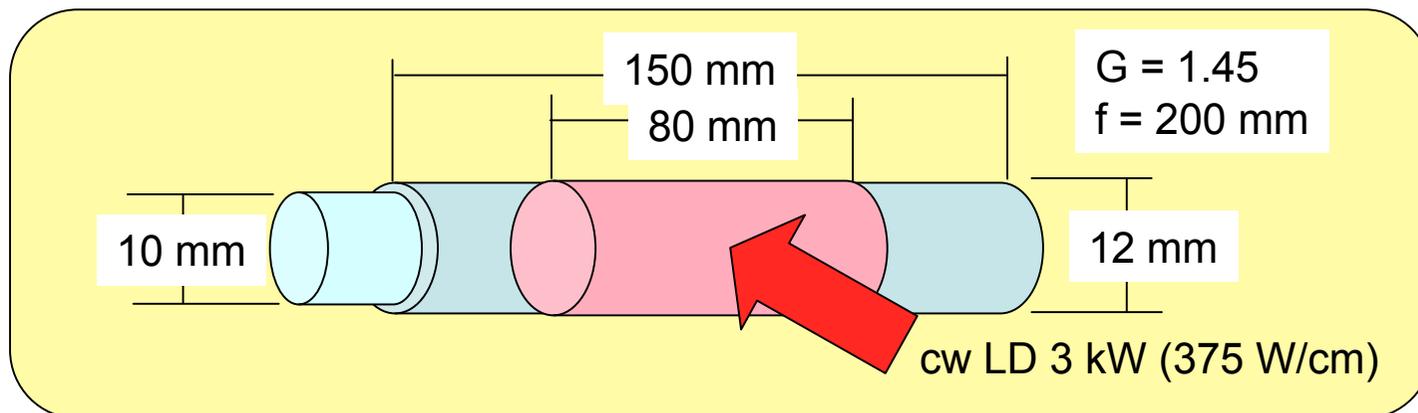
Rod: 10 -13 mm \square , 150 mmL

LD: 6 x 750 W, 200 μ s, < 2.5 kHz

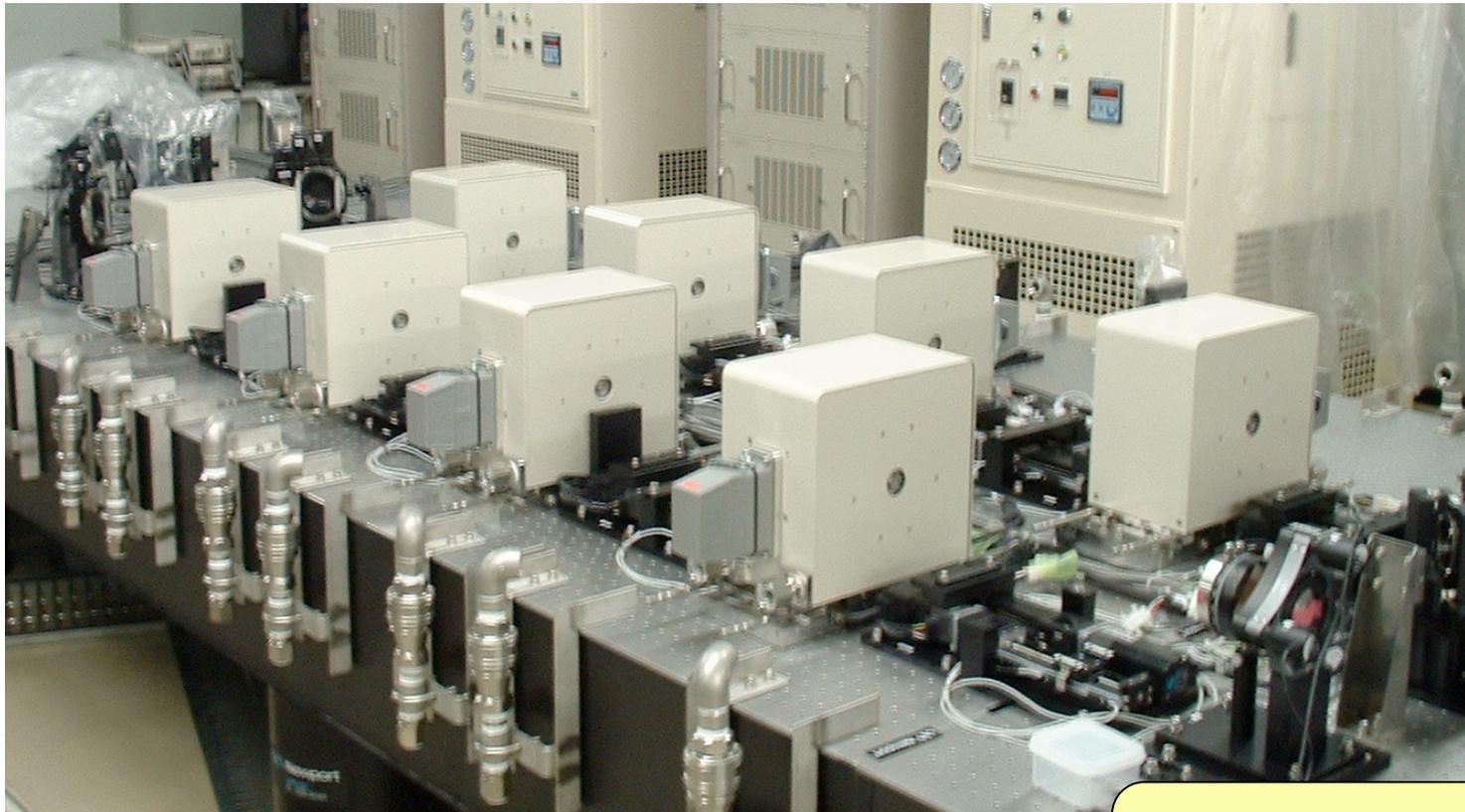


Summary (Test Amplifier Module)

- / Uniform pumping was achieved by adjusting several parameters.
- / Diameter of 12 mm was selected
 - Gain : x 1.45 (at 3.0 kW Pumping)
 - Thermal lens : 20 cm (at 3.0 kW Pumping)
- / Thermal fracture of ceramic YAG rods increased up to 520 W/cm.
- / System analysis suggests that we need 8 amplifier modules pumped at 24 kW to get output power of 5 kW.



Main Amplifier Chain of High Average Power Nd:YAG Laser



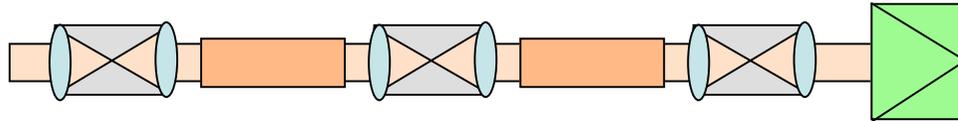
March, 2005

1 J, 3 ns, 5 kHz
5 kW Laser

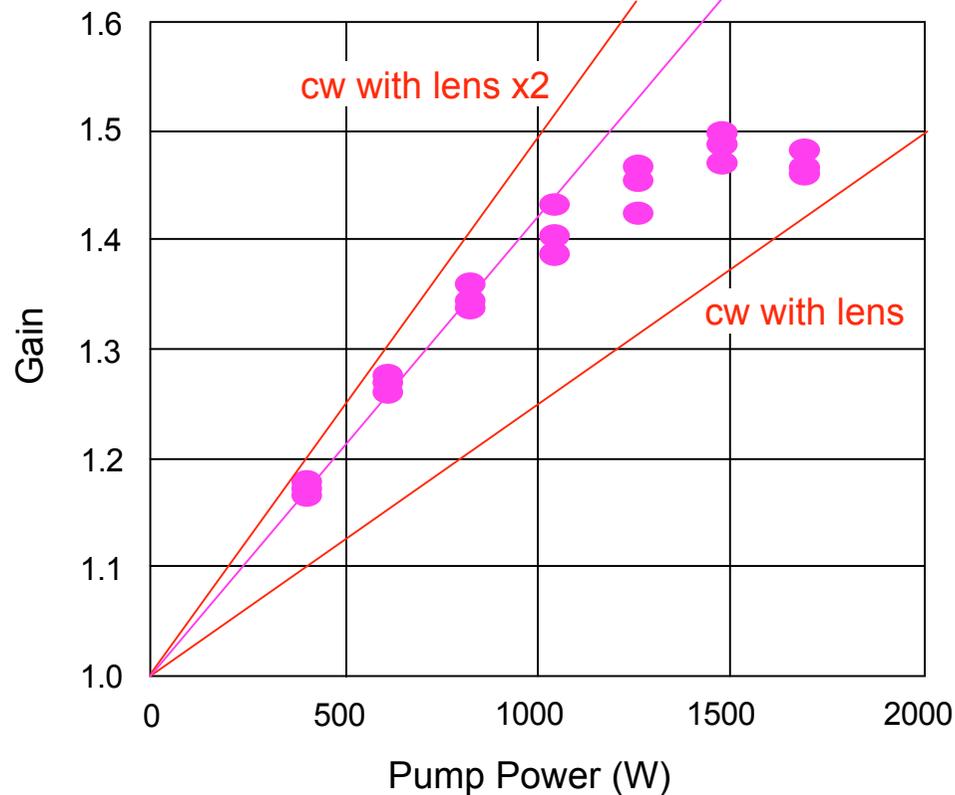


2 Unit Gain Property (12 mm \square , 0.6 at %, with Lens)

From Front-End: a few W, 10 ns, 5 kHz

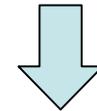


Thermal lens effect is compensated by adjusting distance of spatial filters.



Gain Saturation ??

We checked fluorescence spectrum. Center wavelength sifts according to pump power.

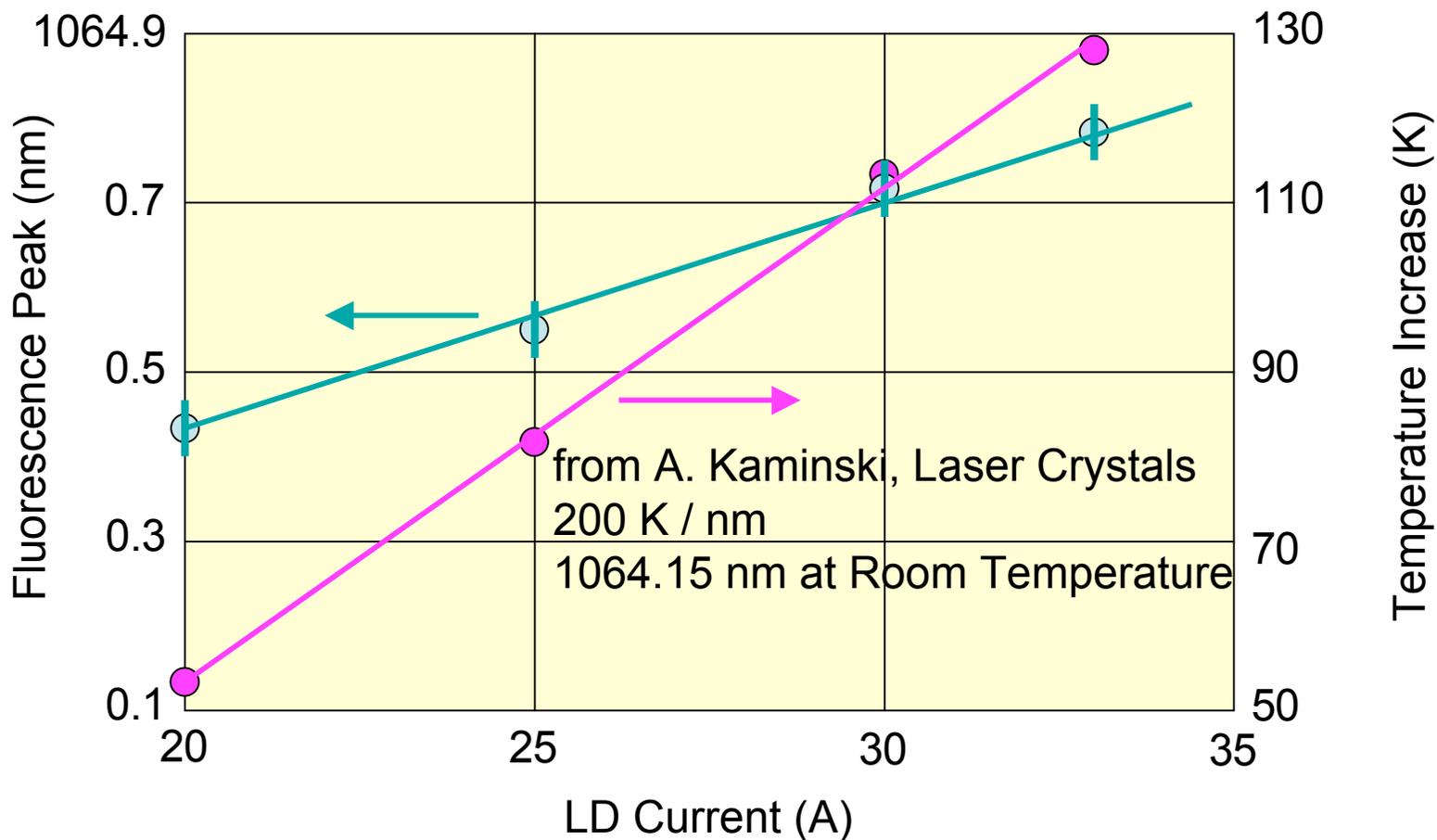


Improvement of cooling system for Nd:YAG rods

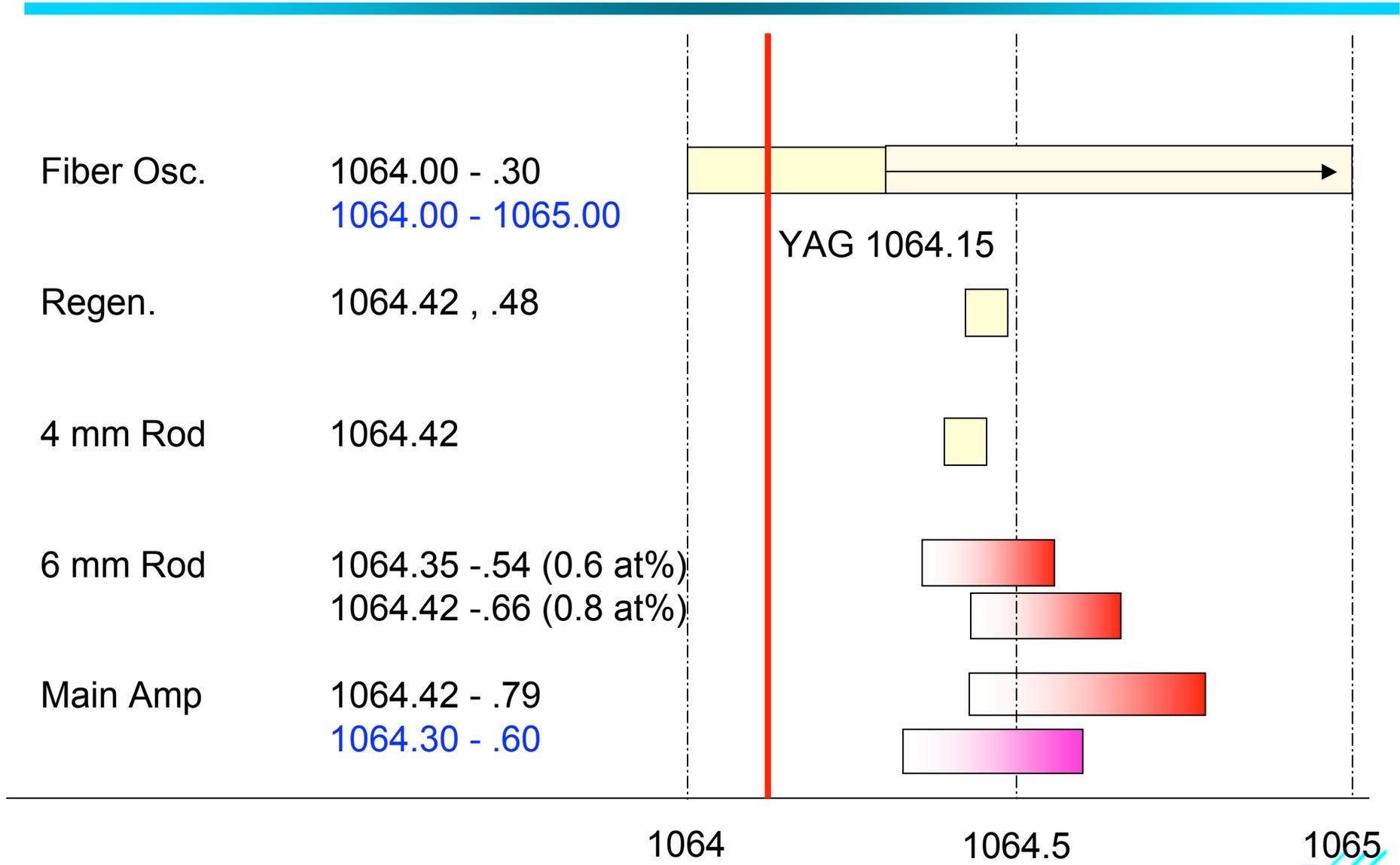


Fluorescence Shift vs Pumping power

Unit 8, 10 μ , 0.8 at%, 805 nm



Wavelength Matching between Osc. and Main Amp.



Optical Arrangement of 2 pass(4 Units) + 1 pass (4 Units)

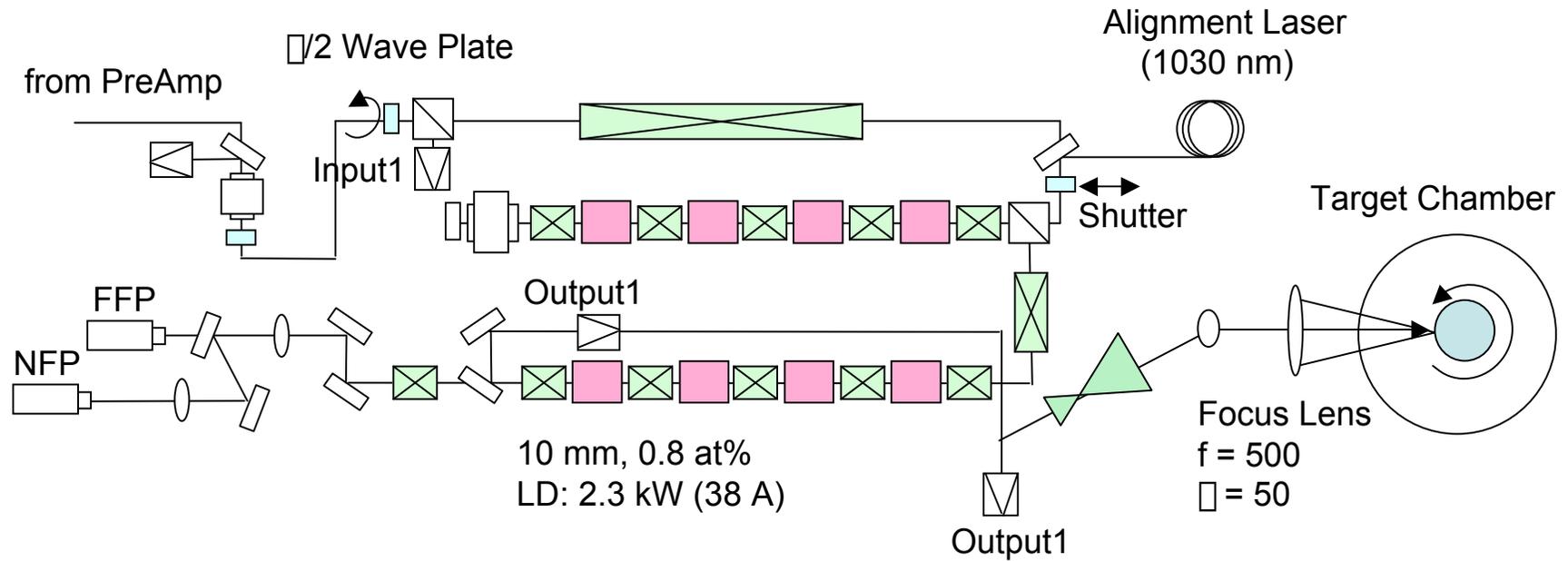
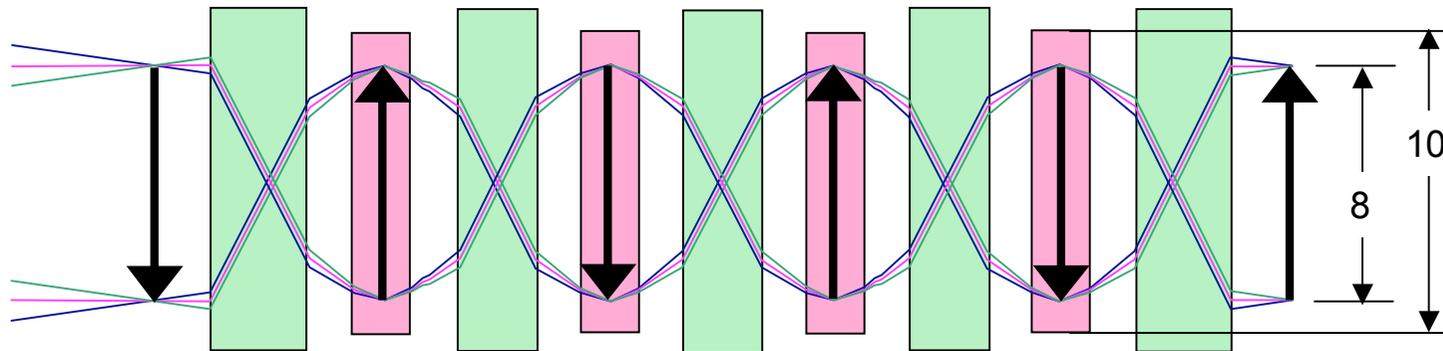
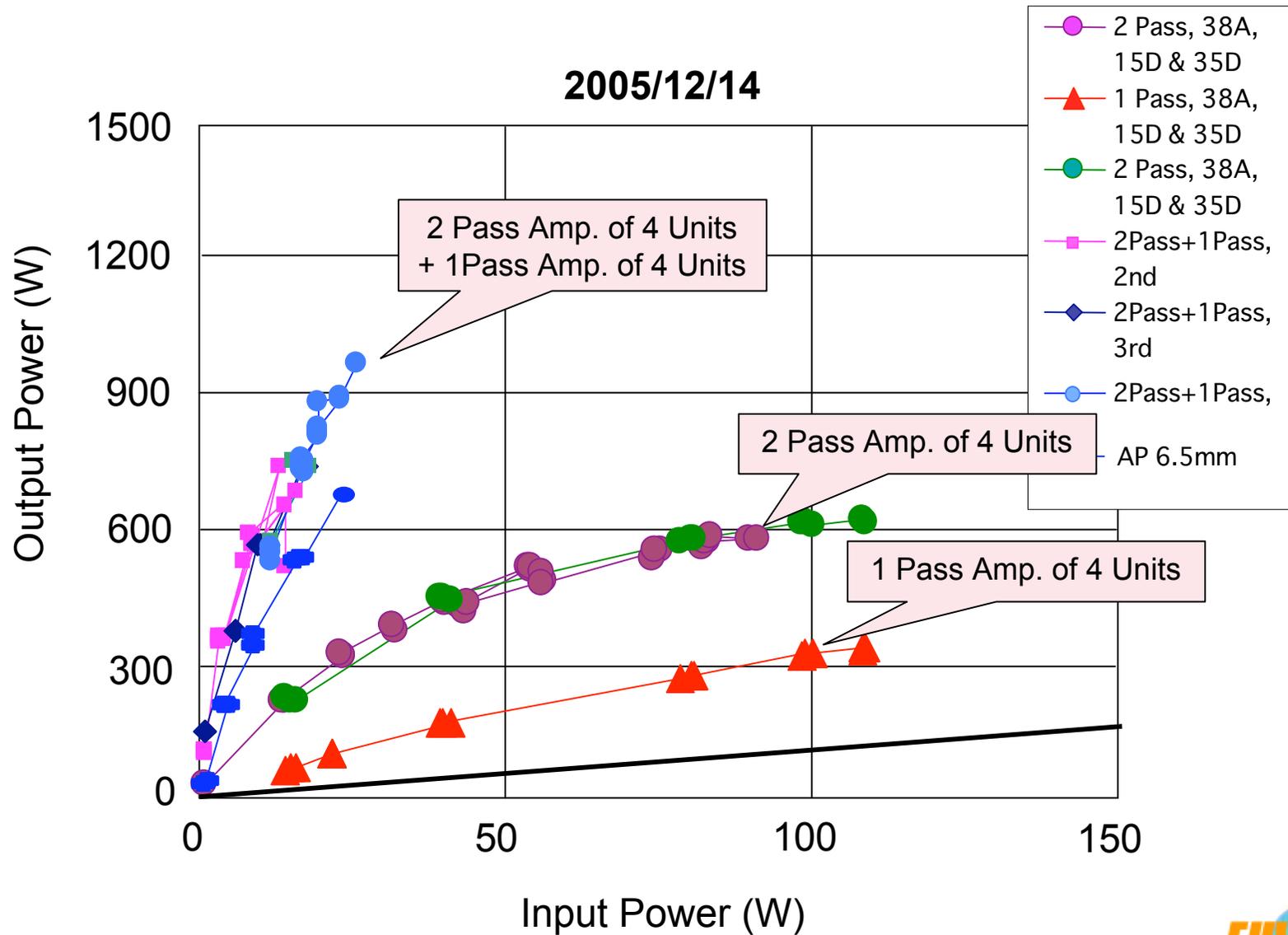


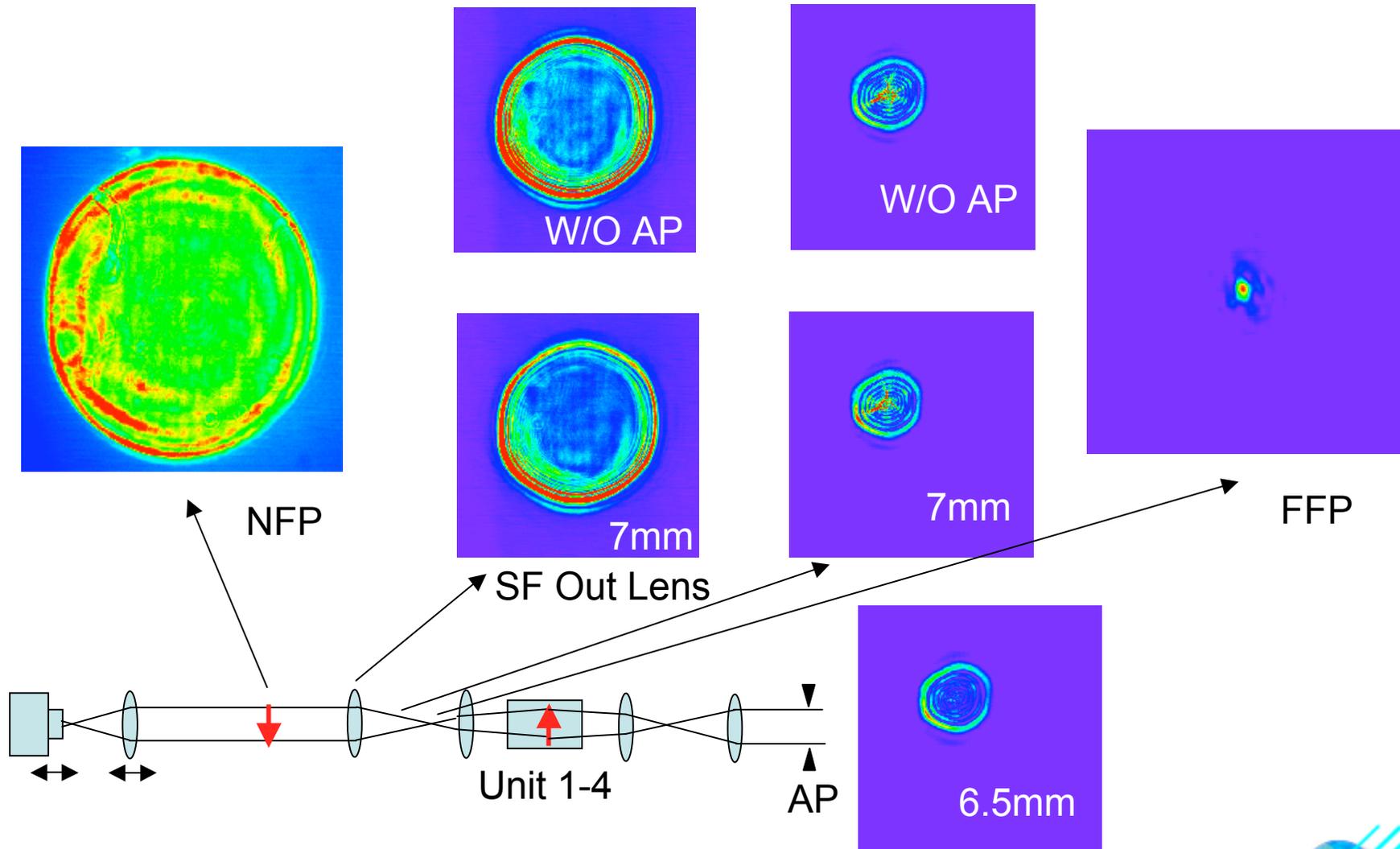
Image Relay and Compensation of Thermal Lens



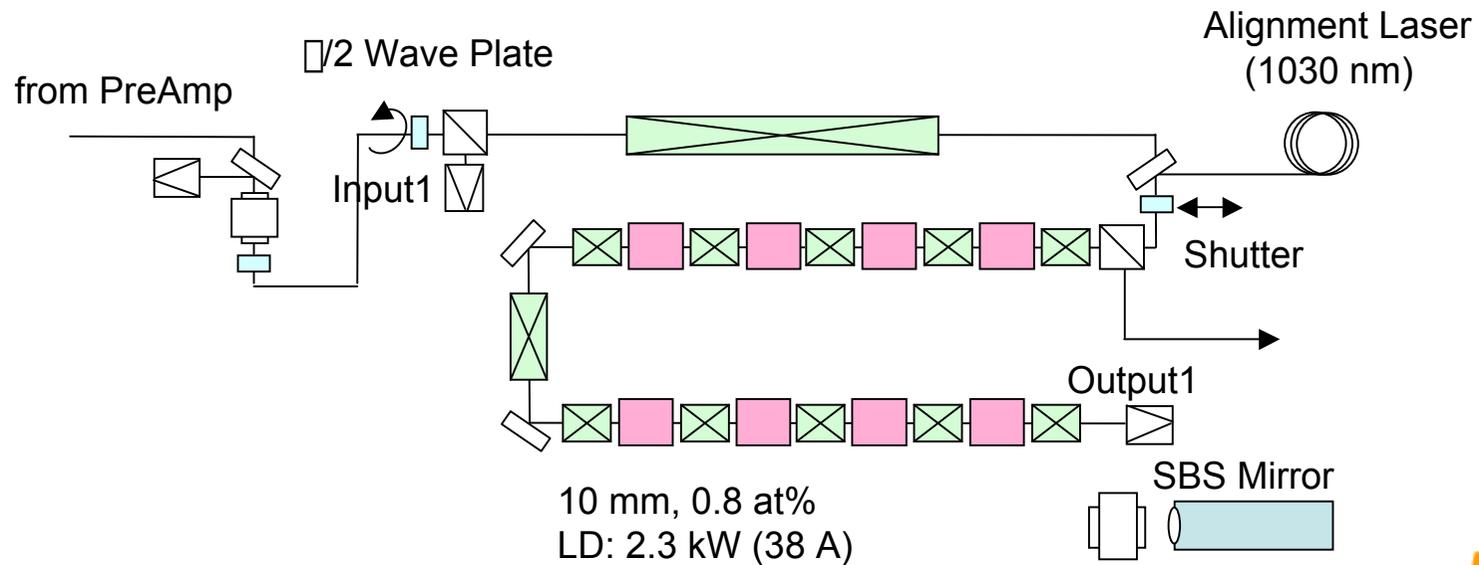
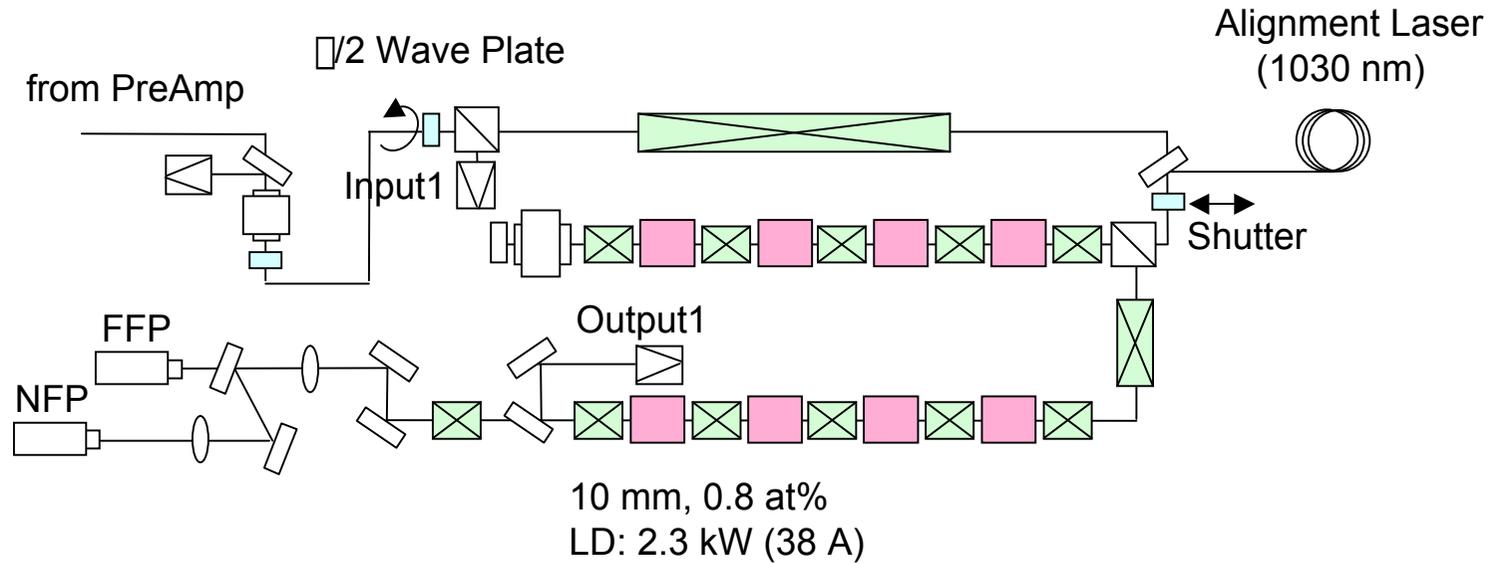
Amplification Results of (4 Unit 2 Pass + 4 Unit 1 Pass)



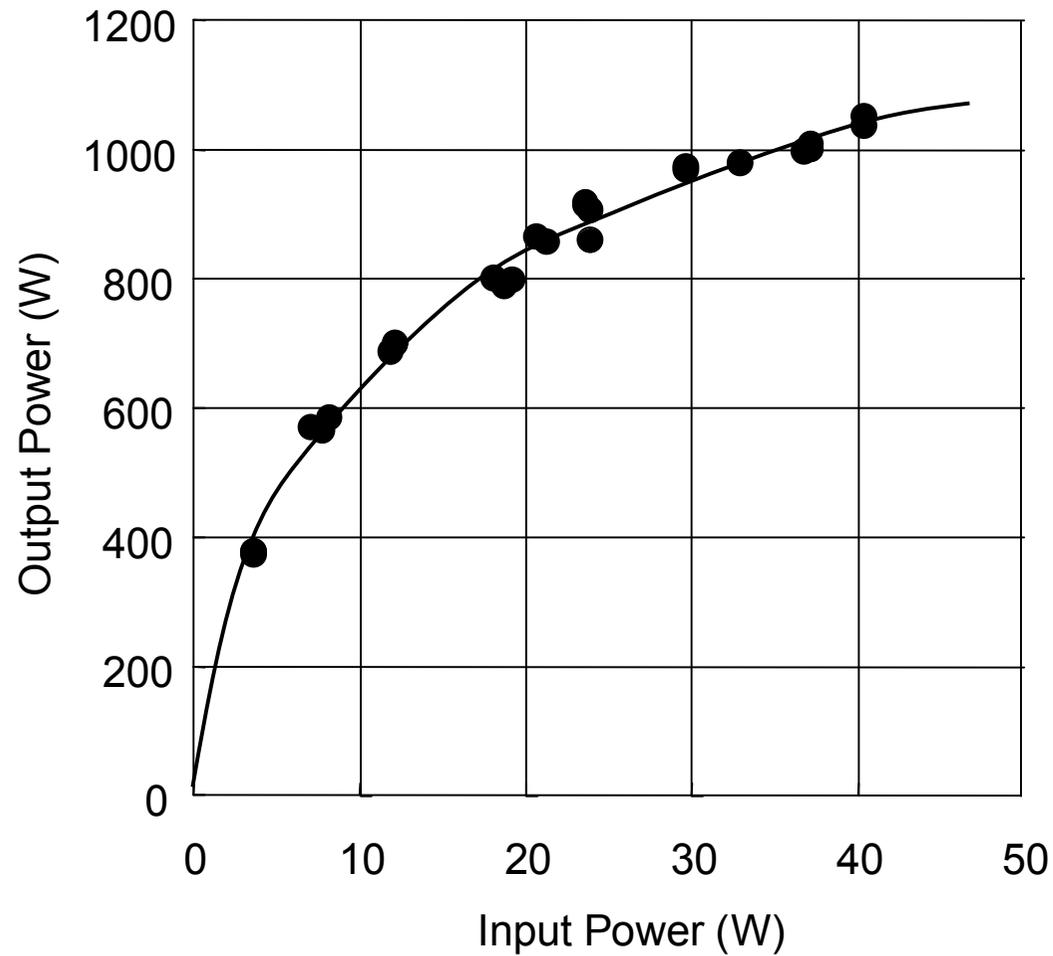
Beam Pattern Measurements



Installation of SBS PC Mirror



Amplification Results of (1 pass Amp. of 8 Units)



Summary

Front-end

- / Stable Single Longitudinal Oscillation 40 mW, Band Width of 100 kHz
- / Switch out by Fast EO Modulator 1.0 - 10.0 ns (Arbitrary Pulse Shape)
- / Fiber Amplifier 740 nJ/3 ns → 1 mJ/3ns

Pre-Amplifier

- / Expected output power was almost obtained. 160 W → 200 W
- / Our concept for compensation of thermal effects was checked.
Further studies are required (ex. Wavefront collection by DM)

Test Amplifier Module

- / Uniform pumping was achieved by adjusting several parameters.
- / Diameter of 10-12 mm was selected. $G = 1.45$, Thermal lens = 20 cm (at 3.0 kW)
- / System analysis suggests that we need 8 amplifier modules pumped at 24 kW to achieve output power of 5 kW.

Main Amplifier Chain

- / All components were installed by the end of Mar. 2005.
- / Output of 1 kW was obtained by 1 pass amplification of 8 Units (at 2.5 kW).
- / Further studies (2 pass amplification, SBS PC Mirror)

